National Aeronautics
and Space Administration

Needs:EDAC montecarlo, poisson montecarlo, scrub of flow
And simplification of material.

Testing for Rare SEEs in FT Devices

Steven M. Guertin

Jet Propulsion Laboratory / California Institute of Technology
Pasadena, CA

(With assistance from Craig Hafer, Steve Griffith, Jim Nagy, and Fred Sievert of Aeroflex)

This work was sponsored by the NASA Electronic Parts and Packaging Program (NEPP)

This work was performed at the Jet Propulsion Laboratory, California Institute of Technology,
Under contract with the National Aeronautics and Space Administration (NASA)

Outline

- Background on RHBD/FT Test Challenges
- Information about UT699
- Test results for a rare event type
- Discuss test and analysis methods for event
- Apply methods to show event is a true SEE
- Conclusions

National Aeronautics
and Space Administration

Goals

- Discuss Microprocessor/SOC testing, focusing on effects in RHBD/FT devices.
- Present a case study of a rare SEE in the Aeroflex UT699 (on the order of 1/100,000 years in GEO).
- Discuss test and analysis methods to identify true SEE rather than overwhelming of FT
- Apply test and analysis methods to verify the rare SEE is a true SEE

National Aeronautics
and Space Administration

Background – What is a Rare SEE?

- ASTM 1192 and JEDEC 89 both indicate that when ruling out an event type, 1e7/cm^2 is a good fluence goal for testing.

- A rare event is one where only a couple occur with this fluence… but it leads the actual space error rate in some environments.

- In RHBD/FT systems these may be hard to test due to difficulties involved in increasing flux.

National Aeronautics
and Space Administration

SEE Testing of SOC/Processors

- Somewhat normal test procedure or flow
  - Measure the cross section for static elements
    - SRAM/Latches/FFs
    - External monitoring (i.e. JTAG) or self-interrogation
    - Minimize impact of dynamic elements and operations
  - Check SOC subsystems for sensitivity of these elements during operation
    - Operate key elements (processor, communication, memory interfaces)
    - Self-interrogation required
    - Establish event cross sections for running code in these subsystems
  - Gather minimal information for key analysis issues
    - Test with altered flux (try for 33+ times over or under – prefer low)
    - Test with altered fluence
    - Test with altered clock
- Analyze data to identify potential anomalies

Anomalies, Test Artifacts, SETs

- Analyze dynamic tests to establish estimated static elements involved
  - I.e. Processor: #total bits in: registers, caches, look up/history tables, and pipeline latches.
  - Then apply an application dependent factor for duty cycle.

- If analysis shows static elements are not the most significant source
  - (Looking for ~10x increase in rates when changing operating conditions – alternate mode, clock rate, flux etc.)
  - Try to identify the following causes:
    - Errors in the test system
    - Flux dependence
    - Fluence dependence
    - SETs – IO interfaces and/or
  - If any were missed during testing, errors were found, or no solution is found, improve test sensitivity and repeat test.
  - If you still don't have a good answer for cause, write a paper.

Impact of RHBD on SEE Testing

- RHBD in digital devices can reduce SEE sensitivity
  - DICE Latch
  - 6-T SRAM Cells
  - SET reduction through filtering
- This impacts test planning
  - Many of the elements we know how to test will no longer upset
  - Multiple SEE sensitivities may turn on at various LETs
  - SEE's leading space event rates may require new test methods

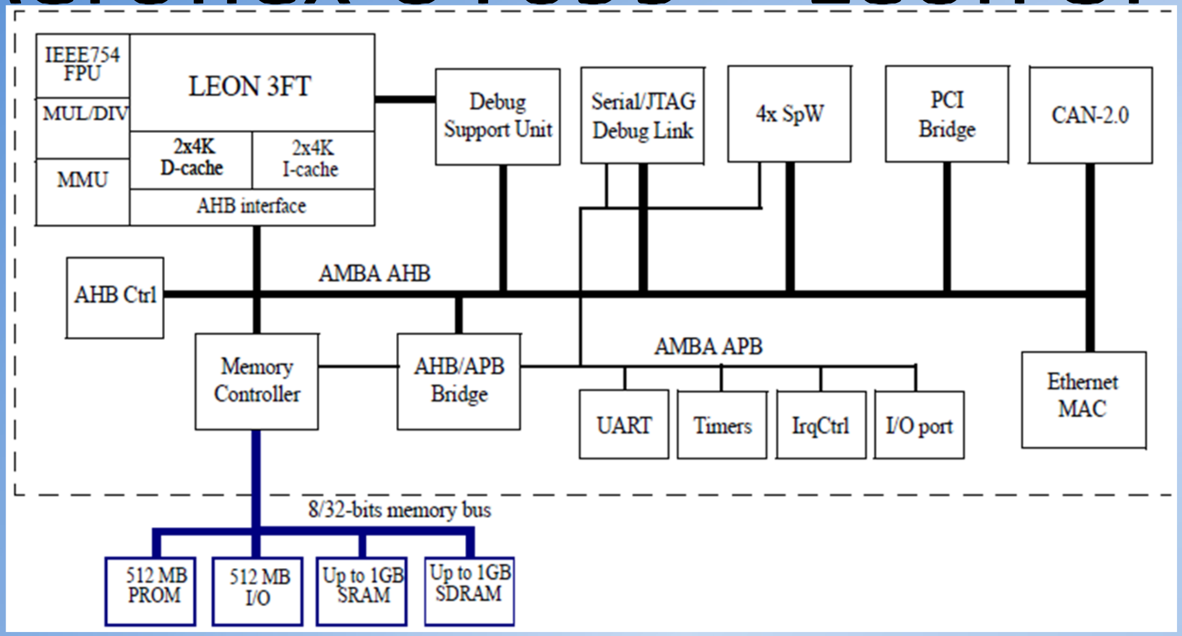
National Aeronautics
and Space Administration

Impact of FT on SEE Testing

- Fault tolerance is used a lot in modern SOC/Microprocessors
  - EDAC and/or parity in on-board caches
  - EDAC on off-chip memories
  - CRC or other checks on communications packets
- Often used on elements with no RHBD
- While testing, event rates in underlying structures may be relatively high
- This impacts test planning
  - Fluence between “scrubbing” must be controlled
  - Intrisic “scrubbing” in many devices is the L1 cache usage, or the duration of a packet transmission, indirectly affecting flux.
  - Test software must support operation of FT and verify it

National Aeronautics
and Space Administration

Aeroflex UT699 – Leon 3FT



- Built with fault tolerance
  - Caches and external memory bus
- And RHBD elements
  - FFs with threshold LET of 54 MeV-cm^2/mg
  - SRAM cells with threshold of about 10 MeV-cm^2/mg

- SEE Data Reported
  - Upsets in FT protected cells reported in 2009 NSREC Data Workshop (Hafer et. al.)
- Chosen for further study
  - Initial testing included some anomalous events
  - Test software not adequate to find out if FT systems overloaded.

National Aeronautics
and Space Administration

Register File EDAC

- FT in the UT699 registers is accomplished with 32/7 EDAC

The EDAC check bit architecture used by the UT699.	
CB0	D0 ^ D4 ^ D6 ^ D7 ^ D8 ^ D9 ^ D11 ^ D14 ^ D17 ^ D18 ^ D19 ^ D21 ^ D26 ^ D28 ^ D29 ^ D31
CB1	D0 ^ D1 ^ D2 ^ D4 ^ D6 ^ D8 ^ D10 ^ D12 ^ D16 ^ D17 ^ D18 ^ D20 ^ D22 ^ D24 ^ D26 ^ D28
CB2#	D0 ^ D3 ^ D4 ^ D7 ^ D9 ^ D10 ^ D13 ^ D15 ^ D16 ^ D19 ^ D20 ^ D23 ^ D25 ^ D26 ^ D29 ^ D31
CB3#	D0 ^ D1 ^ D5 ^ D6 ^ D7 ^ D11 ^ D12 ^ D13 ^ D16 ^ D17 ^ D21 ^ D22 ^ D23 ^ D27 ^ D28 ^ D29
CB4	D2 ^ D3 ^ D4 ^ D5 ^ D6 ^ D7 ^ D14 ^ D15 ^ D18 ^ D19 ^ D20 ^ D21 ^ D22 ^ D23 ^ D30 ^ D31
CB5	D8 ^ D9 ^ D10 ^ D11 ^ D12 ^ D13 ^ D14 ^ D15 ^ D24 ^ D25 ^ D26 ^ D27 ^ D28 ^ D29 ^ D30 ^ D31
CB6	D0 ^ D1 ^ D2 ^ D3 ^ D4 ^ D5 ^ D6 ^ D7 ^ D24 ^ D25 ^ D26 ^ D27 ^ D28 ^ D29 ^ D30 ^ D31

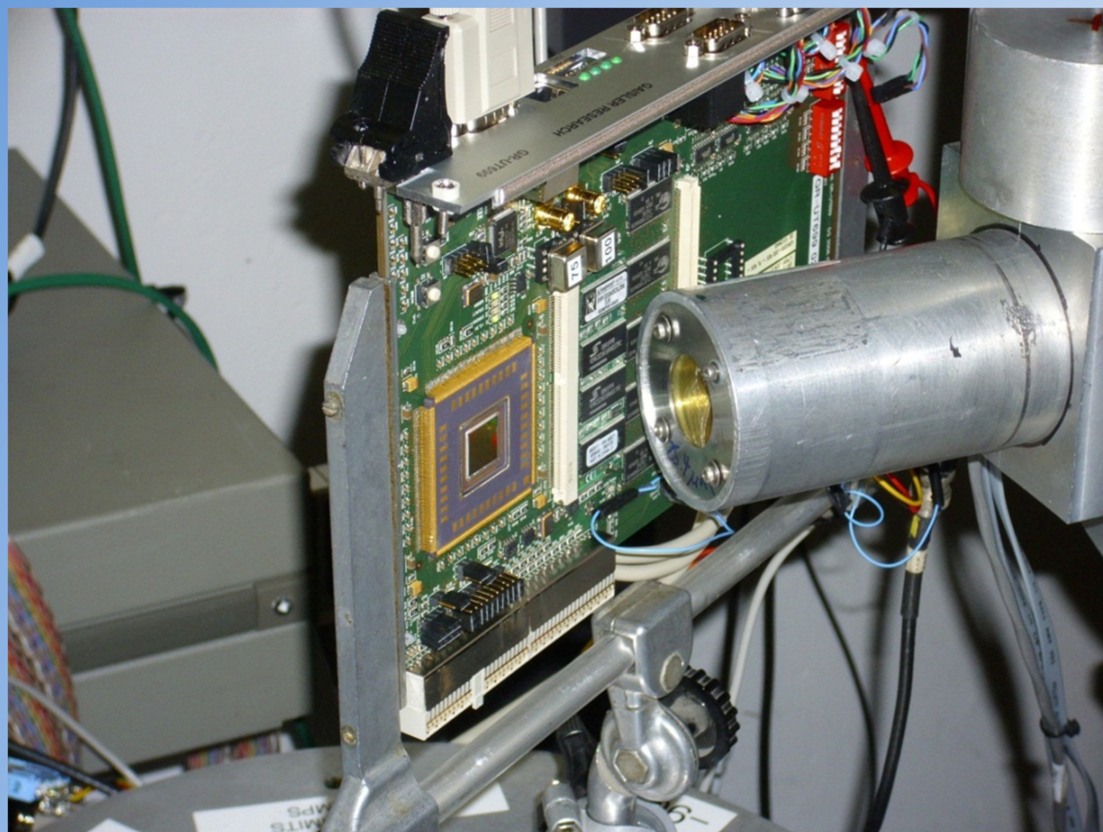
- Four key test patterns
  - All have same check bits
  - 0x0000_0000 and 0xffff_ffff set by code – others seen after SEE

Check Bit Patterns for Test Data Patterns	
Value	Check Bits
0x0000_0000	0b000_1100
0xffff_ffff	0b000_1100
0x0000_ffff	0b000_1100
0xffff_0000	0b000_1100

- The UT699 is also protected with parity bits on the cache lines (1 parity for 8 bits). Errors are silently corrected by re-fetch since the caches are write-through only.

Radiation Testing of UT699

- Testing Performed at TAMU Cyclotron



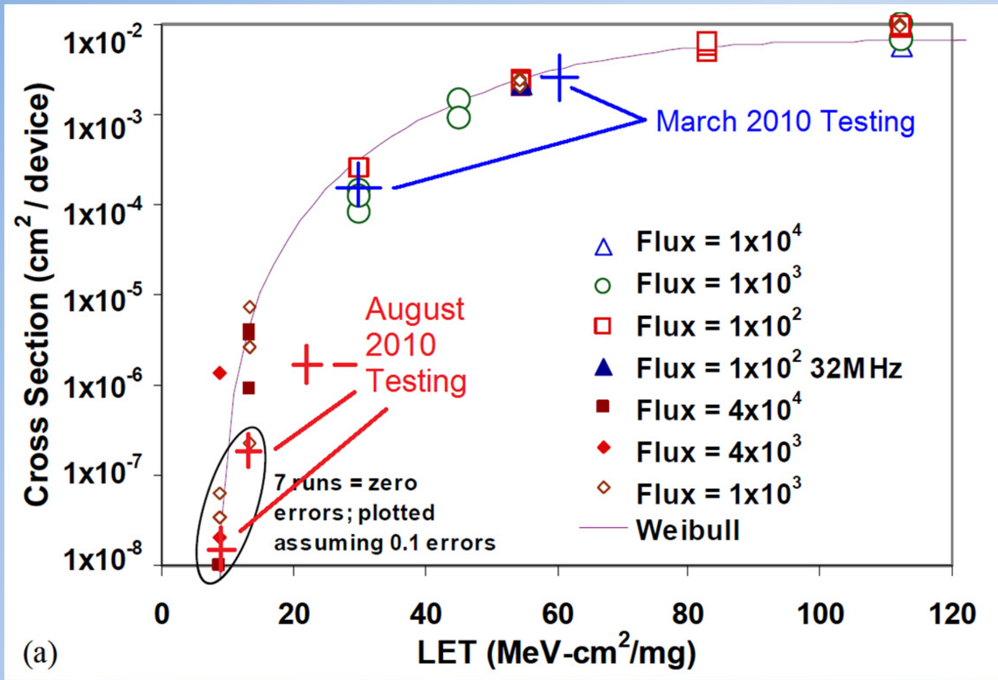
- Tested with Ar and Kr, LET_{eff} = 8.7 to 60 MeV-cm^2/mg
- Tested at V_{core} = 2.3V, V_{IO} = 3.0, and Clk=75 MHz

UT699 SEEs in SRAM and FFs

- Previous testing showed upset sensitivity in static elements… - verified during testing for this work:

Original plot is from 2009 IEEE Radiation Effects Data Workshop, by Hafer et. al.

Additional points are from this testing.



- Previous conclusions about impact of scrubbing apply to the upsets reported in this figure.

Register Testing Anomalies

- In-situ test code was improved to the point where events were identified by the code.
- A non-FT type event was seen at low LET with low cross section (important because at high LET the low cross section would hide it behind FT events).
- The event type was manifest as a “partial” 0’ing of a register.
  - Manifested as 0’ing of a 16-bit field in a register
  - Results in 16-bit “SEU”
  - Or an EDAC uncorrectable
  - (9 extra bits of check unused)

Check Bit Patterns for Test Data Patterns

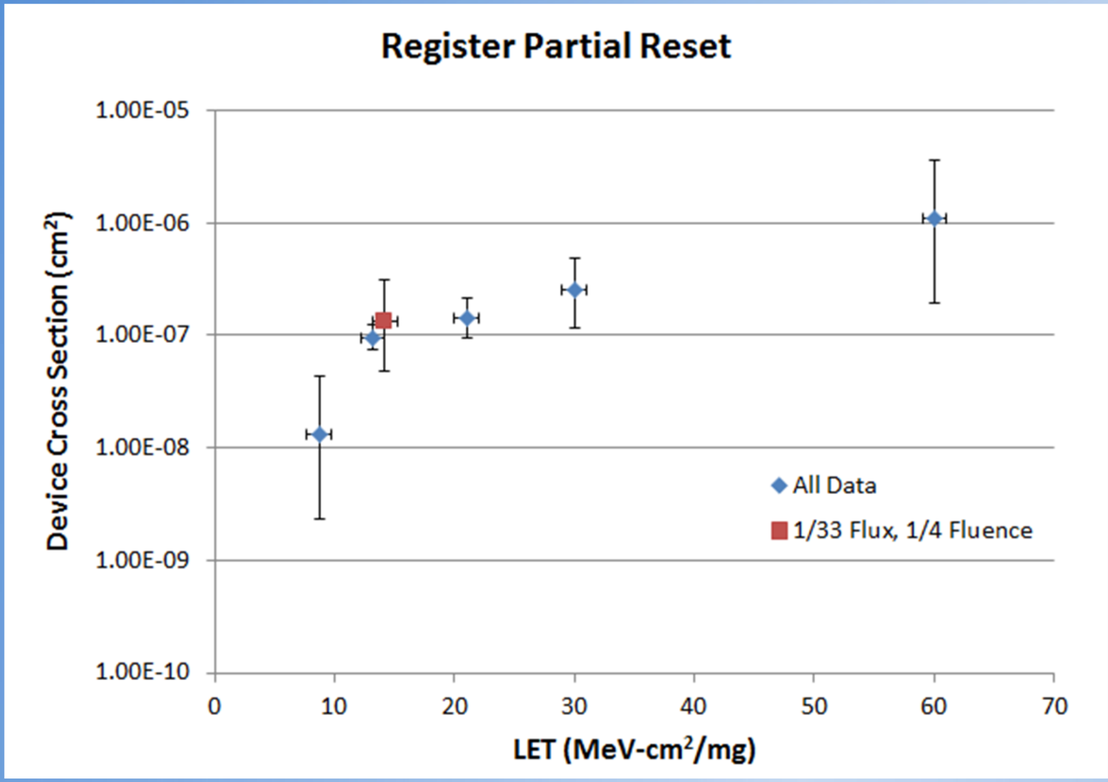
Value	Check Bits
0x0000_0000	0b000_1100
0xffff_ffff	0b000_1100
0x0000_ffff	0b000_1100
0xffff_0000	0b000_1100

- 2^{32} “good” values, $39*2^{32}$ SBE values, means that 40/128 of the 2^{32} data patterns – or 31.5% chance resulting error will cause no system detectable event…

National Aeronautics
and Space Administration

Register Test Anomalies

- Very low cross section, but just high enough to put a thorn in the analysis…



But what if there is flux dependence?
(Test code may depend on FT elements.)

How does the 1/33 flux point impact our understanding?

Should more data have been taken, or is it sufficient to draw conclusions?

Flux Effects – Analysis

- What if partial register 0'ing is coming from a flux dependency?
- High flux cannot prove true SEE if device has flux dependence.
  - Unless test methods are fully able to keep the system healthy during elevated flux, results will be inconclusive
  - Statistics of rare events are such that if there is no flux dependence, the results may still be inconclusive.

National Aeronautics
and Space Administration

Statistical Analysis of Flux Dependence

(assuming no other dependencies)

- Given observation of N_1 & N_2
  - ϕ_i are fluxes, T_i are test periods and τ is dead time per event

$$\sigma_i = \frac{N_i}{\phi_i\left(T_i - N_i\tau\right)}$$

  - Assume $N_i\tau \ll T_i$ (i.e. dead time is small and effect is not saturated)
- Examination of σ_1 & σ_2
  - $\sigma_1 = \sigma_2$ if there is no flux dependence
  - $\sigma_1 / \sigma_2 \propto \phi_1 / \phi_2$ if flux dependent (to first order)
    - (True if dependence is due to two random SEUs in one EDAC word.)
- Two statements (for a given $\phi_1 / \phi_2 = r > 1$) :
  - If N_1 is very similar to N_2, how small must N_2 be for a given N_1 and *r* to be inconsistent when claiming no flux dependence?
  - If N_1 is bigger than N_2, how much bigger must it be to show flux dependence?

National Aeronautics
and Space Administration

Events Required for Statistics, $\phi_2/\phi_1=r > 1$

Maximum N_2 below which flux dependence must be considered, for r = 30 and N_1 given below.

N_1 (r=30)	N_2 (90%)	N_2 (95%)	N_2 (99%)
10	2	n/a	n/a
15	6	2	n/a
20	10	7	1
25	14	11	3
30	19	15	11
40	29	25	20
50	39	35	30
70	55	51	45
N>70	$N-1.81\sqrt{N}$	$N-2.16\sqrt{N}$	$N-2.88\sqrt{N}$

Minimum N_2 above which (proportional) flux dependence must excluded, for r = 30 and N_1 given below.

N_1 (r=30)	N_2 (90%)	N_2 (95%)	N_2 (99%)
10	n/a	n/a	n/a
15	2	n/a	n/a
20	4	1	n/a
25	14	11	3
30	19	15	11
40	29	25	20
50	39	35	30
70	55	51	45
N>70	$N-1.81\sqrt{N}$	$N-2.16\sqrt{N}$	$N-2.88\sqrt{N}$

- Assumes same fluence - 30x longer test time at low flux…
- Results derived using Monte Carlo simulations
- Values are conservative for *r*>30 on left, and *r*<30 on right.
- 3 confidence levels given, using 2-sided tails, so 5%, 2.5%, and 0.5% tails were used
  Confidence levels indicate likelihood of error when adopting table statements.

National Aeronautics
and Space Administration

Events Required when Fluence Reduced

Maximum N_2 below which flux dependence must be considered, for r = 30 and N_1 given below.

N_1 (r=30)	N_2 (90%)	N_2 (95%)	N_2 (99%)
5	2	n/a	n/a
8	6	2	n/a
10	10	7	1
15	14	11	3
20	19	15	11
25	29	25	20
30	39	35	30
40	55	51	45
N>49	$N-1.81\sqrt{N}$	$N-2.16\sqrt{N}$	$N-2.88\sqrt{N}$

Minimum N_2 above which (proportional) flux dependence must excluded, for r = 30 and N_1 given below.

N_1 (r=30)	N_2 (90%)	N_2 (95%)	N_2 (99%)
5	n/a	n/a	n/a
8	2	n/a	n/a
10	4	1	n/a
15	14	11	3
20	19	15	11
25	29	25	20
30	39	35	30
40	55	51	45
N>49	$N-1.81\sqrt{N}$	$N-2.16\sqrt{N}$	$N-2.88\sqrt{N}$

- Picked fluence difference of 10x for realistic test scenarios.
- Results derived using Monte Carlo simulations
- Values are conservative for *r*>30 on left, and *r*<30 on right.
- 3 confidence levels given, using 2-sided tails, so 5%, 2.5%, and 0.5% tails were used
  Confidence levels indicate likelihood of error when adopting table statements.

National Aeronautics
and Space Administration

Application of Statistics on Register Clobber

- Measured at 1 LET (13.2 MeV-cm^2/mg)
  - At fluence = $1.5\times10^7/cm^2$
    - 2 events at flux = $3.3\times10^3/cm^2$
  - At fluence = $1.5\times10^8/cm^2$
    - 12 events at flux = $1\times10^5/cm^2$
- For these numbers of events we cannot reject the possibility that there is no flux dependence. (Low flux appears to give <u>higher</u> cross section.)
- We can reject linear flux dependence if N_2 (2 in this case) is above 1 with 95% confidence… so we reject the linear flux dependence option.

Conclusions

- RHBD and FT devices require special test considerations
  - Devices may require in-situ operation
  - Many event types will have low cross section
  - FT structures get overwhelmed during testing
  - SET sensitivities may lead fundamental upset modes
- UT699 was found to have a low rate SEE
  - Event type was partial reset of registers
  - Difficult to find because of FT and complexity of test software
  - Likely to lead event rate (<1/100,000 years) in low GCR orbits
- Statistical analysis necessary to determine if events are true SEE or overwhelming of FT
  - Evidence of flux dependence does not prove all events are due to overwhelming FT
  - Partial 0'ing of registers showed to be inconsistent with overwhelming FT

National Aeronautics
and Space Administration

Backup: Why do MC simulation?

- We are attempting to compare two measurements, one or both of which may involve a small number of counts.
- Estimators for the mean of a Poisson distribution from a small number of observed events N are not handy functions:
  - I.e. let P be probability of accepting an incorrect value, P = 1-C.I. – i.e. for 95% CI, P = 0.05, then:
  - CI = (qChi-Sq(P/2,2*N)/2,qChi-Sq(P/2,2*(N+1))/2)
  - qChi-Sq is the inverse Chi-Sq cumulative distribution function (requires calculation of inverse regularized gamma function)
- Going to the impact of comparing 2 measurements and applying the full formalism is less valuable than explaining the MC techniques.

See also:
http://www.math.mcmaster.ca/peter/s743/poissonalpha.html,
http://statpages.org/confint.html
F Garwood, "Fiducial Limits for the Poisson Distribution" *Biometrica* **28**:437-442, 1936.

Backup: Flux Effects – Testing

- Flux can impact testing, especially when testing fault-tolerant devices or test systems (FT test system refers to scrub intervals or similar software loop periods).

Backup: Fluence Effects

- Fluence build up can affect testing if hidden control bits can upset, or tests are dependent on “soaking”.
- Hidden control bit sensitivity is possible, but somewhat contrived.
- But tests are often based on soaking, even when not intended – for example, self-test code often assumes